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Sandia Third-Party Witness Test of UniEnergy Technologies 1 MW / 3.2 MWh Uni.System™

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Sandia Third-Party Witness Test of UniEnergy Technologies 1 MW / 3.2 MWh Uni.System^{TM}

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Sandia National Laboratories performs third-party witness testing for energy storage systems installed on the electrical grid. Witness testing verifies that the energy storage system that is installed can meet its performance specifications through a thorough evaluation which includes testing, document review, and physical inspection. This document contains the results for the Sandia National Laboratories witness test on the UniEnergy Technologies 1 MW / 3.2 MWh vanadium flow battery known as the Uni.System^{TM}.

ACKNOWLEDGMENTS

This work was funded by the Department of Energy Office of Electricity Energy Storage Sandia would like to acknowledge UniEnergy Technologies for performing all the test on the Uni.System^{TM} and providing all the data to Sandia.

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NOMENCLATURE

UET	UniEnergy Technologies
SOW	Statement of Work
SEL	Schweitzer Engineering Laboratories
PCS	Power Conditioning System
HMI	Human Machine Interface
PPE	Personal Protective Equipment
PCC	Point of Common Coupling
THD	Total Harmonic Distortion
I_{SC}	Short Circuit Current

1. INTRODUCTION

This report is the Sandia National Labs' third-party system evaluation of the 1 MW / 3.2 MWh Avista installation. This evaluation was performed as part of the contracted 2.2 MW Uni.System^{TM} that will be installed at the SnoPUD Everett substation. The SnoPUD project is outlined in Section 2.2 of the Statement of Work (SOW) in the existing contract between 1Energy and UniEnergy Technologies (UET).

1.1. Scope

Sandia was tasked to witness and evaluate the operation of the 1MW / 3.2MWh Uni.System^{TM} AC energy storage system that is installed on the Schweitzer Engineering Laboratories (SEL) campus in Pullman, WA.
Tasks included the following:

- Review UET test plan
- Review system installation at the site, including:
    - Physical arrangement of system components
    - Verify metering points and data recording and monitoring capabilities
- Physically witness tests during operation for 2 days on-site
- Review test data and deliver results

Data collected from the tests were used by Sandia to determine if the Uni.System^{TM} performed as per the system performance specifications provided to Avista and if it met the performance metrics of the PNNL/SNL testing protocol [2]. Performance specs for the UET Uni.System^{TM} are shown in Error! Not a valid bookmark self-reference..

Table 1 - UET Uni.System^{TM} Performance Specifications

Parameter	Value
Nameplate and Peak Power, AC	1 MW, 1.2 MW
Maximum Energy, AC	3.2 MWh
Rated Power: Discharge Duration, AC	1 MW: continuous cycling, 1 MW @ 2 hr, 640 kW @ 4 hr, 520 kW @ 6.2 hr
Efficiency	65-70% AC round trip at the inverter
Self-Discharge	< 2% in standby mode
Cycle Life	Unlimited cycles within system design life
System Design Life	20 years
DC Voltage Range	465 V_{dc} – 1000 V_{dc}
AC Voltage Output	Medium Voltage (4,160 V_{ac} – 34.5 kV_{ac})
Power Factor Range	Available Option
Power Control Modes	Dispatch and Autonomous, 50 ms response time
Communications & Data Protocols	DNP 3.0 or IEC 61850
Ambient Temperature	-40°C to 50°C, active cooling for extended operation >35°C

System Footprint	2,173 ft^2 (assuming 2 rows of 5 containers with doors facing a common 13 ft aisle)

1.2. Technology

Figure 1 - 1 MW / 3.2 MWh UET Uni.System™ at Pullman, Washington

The Uni.System™ is a vanadium flow battery that is rated for 1.2 MW / 3.2 MWh. The system consists of two battery strings. Each string is housed in four 20 ft shipping containers with a fifth container on each string that contains the 600 kW power conditioning system (PCS). The DC input of the PCS has a nominal V_{dc} operating range of 465 V_{dc} – 1000 V_{dc}. Each PCS outputs 283 V_{ac} which is then stepped up 13.8 kV through a 600 kVA transformer. The 13.8 kV output from the transformers is then electrically connected to a Trayer automatic transfer switch which is part of the Avista 13.8 kV electrical distribution system.

Each of the 20 ft containers has three stacks connected in series. The battery management system for each battery string is located in the PCS container and is controlled locally through a human machine interface (HMI) or remotely through a UET site controller. The site controller is located in a small building known as the panel house approximately 20 ft from the Uni.System™ PCS containers.

Figure 2 - Nameplate for single Uni.System^{TM} battery container

Figure 3 - Uni.System^{TM} battery management system HMI

1.3. Review Test Plan

Sandia reviewed the witness test document (Witness Test – REV 1.2.pdf) developed by UET. Tests outlined in the witness test document were determined to adequately evaluate the physical operation of the Uni.System^{TM}, including safety control logic and component functionality. Parameters that Sandia was not able to verify in the Uni.System^{TM} performance specification (Sandia was tasked to witness and evaluate the operation of the 1MW / 3.2MWh Uni.System^{TM} AC energy storage system that is installed on the Schweitzer Engineering Laboratories (SEL) campus in Pullman, WA.
Tasks included the following:

- Review UET test plan
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- Physically witness tests during operation for 2 days on-site
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Data collected from the tests were used by Sandia to determine if the Uni.System^{TM} performed as per the system performance specifications provided to Avista and if it met the performance metrics of the PNNL/SNL testing protocol [2]. Performance specs for the UET Uni.System^{TM} are shown in Error! Not a valid bookmark self-reference..

Table 1) included Self-Discharge, System Design Life and Power Control Mode response time. These parameters were not verified due to either the tests outlined in the witness test did not address these parameters, or data recording equipment was not at a high enough sampling rate. Also, it should be noted that Self-Discharge as well as the Power Control Mode response time of 50 ms is usually verified during factory acceptance testing. However, the Self-Discharge of less than 2% is calculated by UET as the solution in the stack discharged through the membrane. Since the solution in the tanks maintains a constant level, the Self-Discharge is calculated by the electrolyte in each stack multiplied by number of stacks and then divided by the total volume of electrolyte per container. There are three stacks per container and each can hold up to 150 L of electrolyte while the container itself has a total volume of 23,000 L. Calculation for the Self-Discharge is shown in Equation 1.

$$\boldsymbol{SD = \frac{Stack_{NUM} * Stack_{VOL}}{Container_{VOL}} * 100\% = \frac{3 * 150}{23000} * 100\% = 1.9\%} \qquad \textbf{Equation 1}$$

<u>Parameters:</u>
$Stack_{NUM}$ = total number of stacks in one Uni.System^{TM} container
$Stack_{VOL}$ = volume of electrolyte in one stack within a Uni.System^{TM} container, (L)
$Container_{VOL}$ = total volume of electrolyte in one Uni.System^{TM} container, (L)
SD = Self Discharge,(%)

1.4. Review Testing Activity At Site

During the Sandia site visit, the physical arrangement of system components were verified through visual inspection and compared to the Uni.System^{TM} construction drawings. Proper personal protective equipment (PPE), safety documents (Uni.System^{TM} Hazard Awareness and Response), hazard signs, hazard mitigation and emergency response equipment were verified by Sandia through physical inspection. Hazard items verified included installed hazard mitigation barriers, hazard signs, emergency response equipment (spill kit, fire extinguisher and eye wash station) and PPE.

Data recording was accomplished through OSI software, which collects data every second, and stores it on a PI server at UET headquarters. On the Uni.System^{TM} battery string 2, a Hioki 9624-50 power quality meter with harmonic recording capability was hooked up to the PCS at the point of common coupling (PCC). Harmonics were recorded for the duration of the witness test. Sandia was not tasked to verify total harmonic distortion (THD) during the witness test, but results are presented in this report.

Figure 4 - Hioki 9624-50 meter installed at one Uni.System^{TM} battery string

2. SAFETY CONTROLS LOGIC TESTS

Safety control logic was tested and verified to ensure all the alarms and events that can cause the Uni.System™ to shutdown were working properly. The checklist from UET for available control logic is shown in Table 2. In each test the Uni.System™ was turned on and placed either in charge, discharge or idle mode. When a fault or an alarm occurred, the Uni.System™ opened up the series contactors, disabled pumps and placed pumps at zero speed. The testing verified that a fault instantaneously disconnected the Uni.System™ from the electrical grid through a breaker located in the PCS container and disabled all pumps.

Most of the alarms are based on sensor inputs, which have a maximum and minimum tolerance set in the battery management system. To simulate most of the safety control logic tests, the parameters were set to a value that was within the system specification which would be triggered while the Uni.System™ was in normal operation. For example, if the Uni.System™ would fault on a high temperature of 100°F, this value would be lowered in the tolerance settings to 80°F so the alarm would be triggered and the Uni.System™ would fault. Safety control logic tests that were simulated are denoted as such in the Test Method section of Table 2.

Sandia was only present during the Liquid Leak test and the E-Stop; the other tests were performed before the Sandia site visit. Tests performed by UET without Sandia presence were documented by UET, and are not part of this report.

Table 2 - Safety Control Logic Test Matrix

No.	Alarm or Fault	Test Method	Test Result
1	Liquid Leak	Physically place water at the 3 leak sensors per container	System performed a successful fault
2	Pressure Mismatch	Not tested at site. Was tested at factory	None
3	Overcharged Shutdown (High SOC)	Simulated	Successful Test documented by UET
4	High Temperature	Simulated	Successful Test documented by UET
5	High Pressure	Simulated	Successful Test documented by UET
6	High Cell Voltage	Simulated	Successful Test documented by UET
7	High Flow Rate	Simulated	Successful Test documented by UET
8	PCS Trip	Simulated	Successful Test documented by UET
9	High Cl_2 Level	Simulated	Successful Test documented by UET
10	High H_2 Level	Simulated	Successful Test documented

			by UET
11	E-Stop Button	Physically pressed the outside E-Stop on the PCS container	System performed a successful fault

3. SYSTEM CAPACITY TEST

System capacity is the amount of energy that a system can store as well as discharge at a certain power rating for a specific duration. As the power rating is increased, the duration decreases and this relationship is not necessarily linear and can vary drastically from one electro-chemistry to the next. For the Uni.System^{TM} system capacity test, three tests were performed, each having different kW discharge commands and durations that are stated in the performance specification above as well as Table 3.

Table 3 - System Capacity Test Parameters

Test	Discharge Power (kW)	Estimated Charge time (hours)	Estimated Discharge time (hours)
1	520	7.3	6.2
2	640	6	4
3	1000	5.3	2

During these tests, the site controller was used to perform the discharge and charge cycles. Since the site controller does not inherently have a cycling function, a square charge-discharge profile was developed by UET and programmed into the site controller. Figure 5, Figure 6 and Figure 7 show the square charge-discharge profiles that were run through the site controller. For each square charge-discharge profile, the test was repeated three times.

As part of the site controller logic, the voltage and SOC was limited automatically during testing. When the Uni.System^{TM} encountered a voltage limit, it would automatically enter into constant voltage mode. When 100% SOC was reached by the Uni.System^{TM}, the power output is set to zero to prevent the batteries from being over-charged.

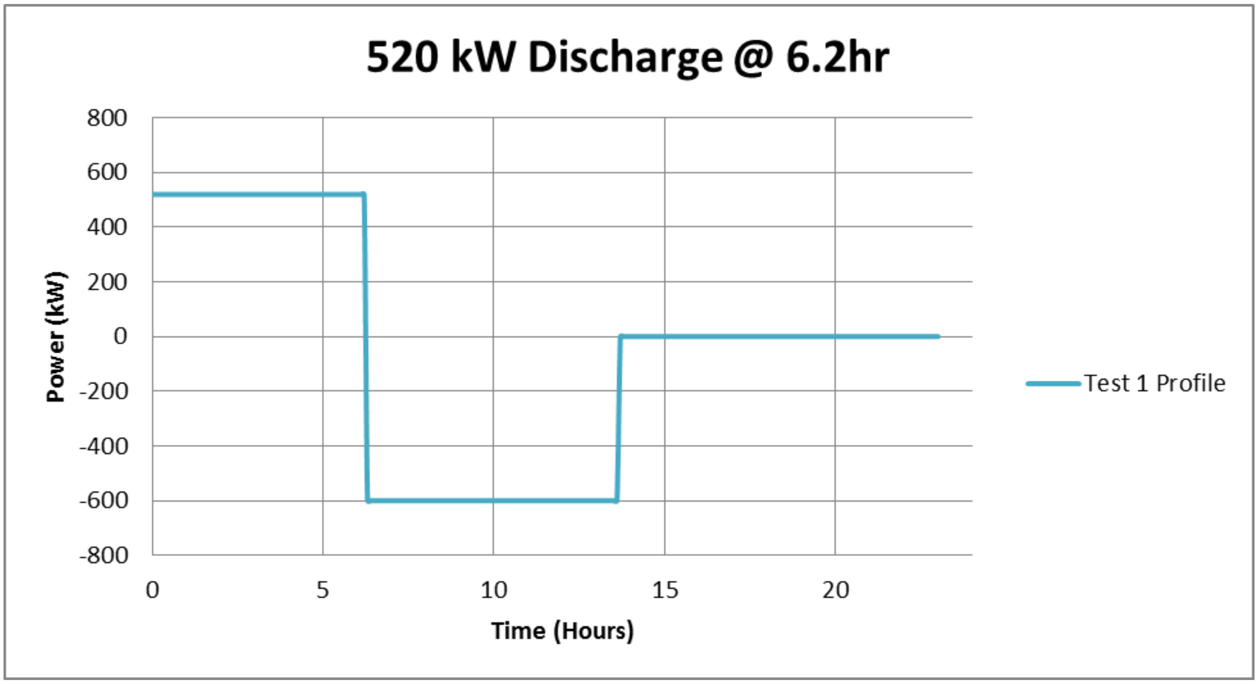

Figure 5 - Test 1 520 kW charge-discharge profile

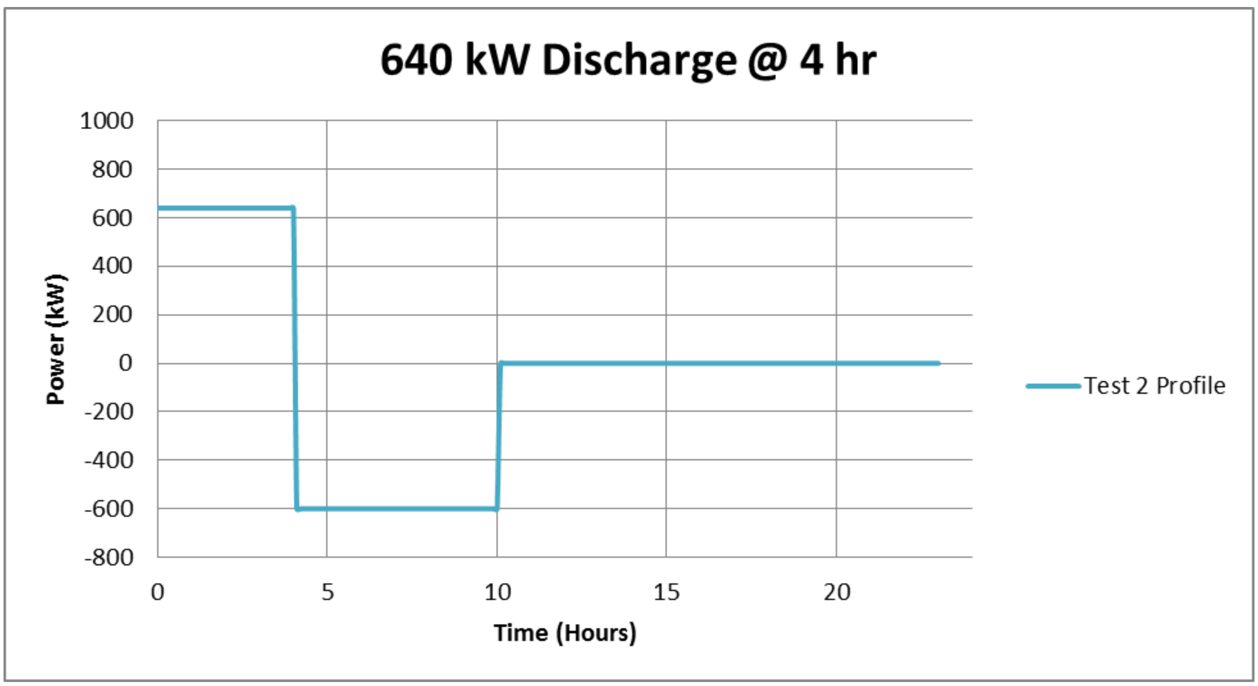

Figure 6 - Test 2 640 kW charge-discharge profile

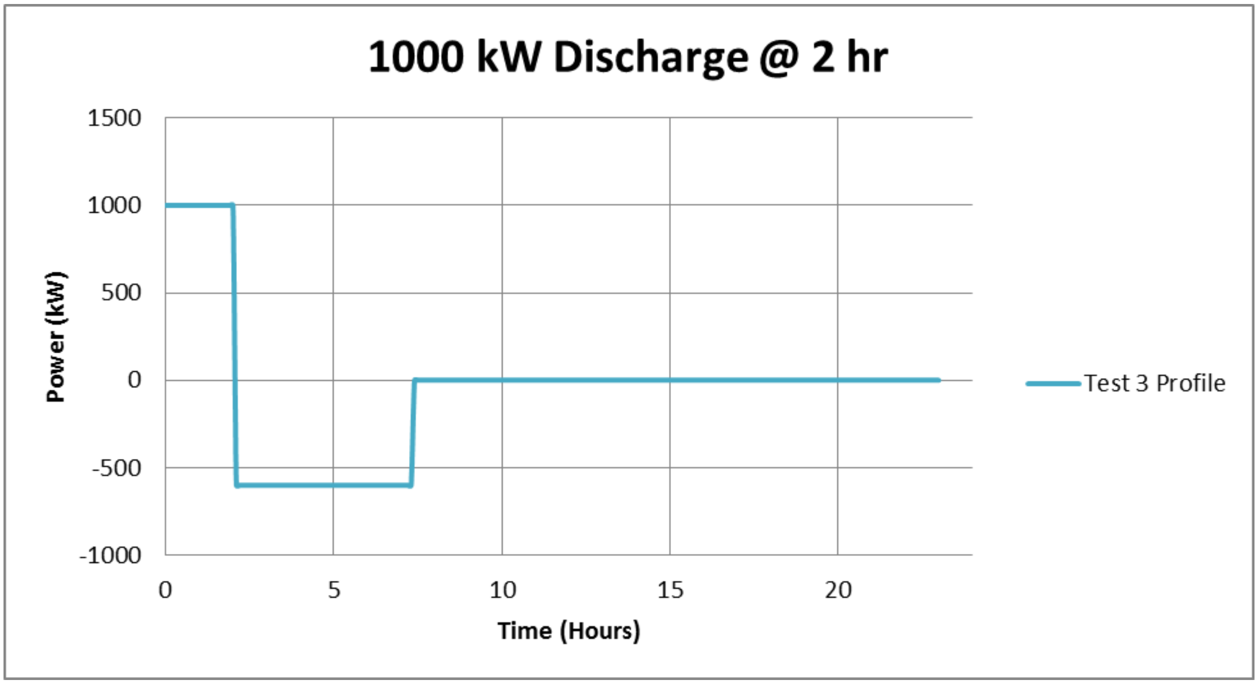

Figure 7 - Test 3 1000 kW charge-discharge profile

3.1. System Capacity Test Procedure

1. Charge Uni.System™ to 100% SOC
2. Program and run Test 1 Profile (520 kW) into the site controller
3. Record start time of test
4. Once Test 1 Profile has completed, confirm that the Uni.System™ is at 100% SOC. Manually recharge the Uni.System™ if SOC is not 100%
5. Record time and verify that data has been captured by the OSI PI data historian
6. Allow Uni.System™ to rest for at least 30 minutes
7. Repeat steps 2-6 until 3 cycles have been performed
8. Charge Uni.System™ to 100% SOC
9. Program and run Test 2 Profile (640 kW) into the site controller
10. Record start time of test
11. Once Test 2 Profile has completed, confirm that the Uni.System™ is at 100% SOC. Manually recharge the Uni.System™ if SOC is not 100%
12. Record time and verify that data has been captured by the OSI PI data historian
13. Allow Uni.System™ to rest for at least 30 minutes
14. Repeat steps 9-13 until 3 cycles have been performed
15. Charge Uni.System™ to 100% SOC
16. Program and run Test 3 Profile (1000 kW) into the site controller
17. Record start time of test
18. Once Test 3 Profile has completed, confirm that the Uni.System™ is at 100% SOC. Manually recharge the Uni.System™ if SOC is not 100%
19. Record time and verify that data has been captured by the OSI PI data historian
20. Allow Uni.System™ to rest for at least 30 minutes

21. Repeat steps 16-20 until 3 cycles have been performed

3.2. System Capacity Test Results

Results for the system capacity test are shown in Table 4. The energy performance is calculated by the power produced multiplied by the duration that it produced it for shown in Equation 2.

$$E_{d,kWh} = \sum_{i=1}^{X} P_{kW}(i) * \frac{1}{t_{1hr}}, if\ P_{kW}(i) > 0 \qquad \text{Equation 2}$$

Parameters:

E_{kWh} = Energy produced during one cycle test, (kWh)
X = number of time steps in one cycle test
$P_{kW}(i)$ = Power produced by energy storage at time i, (kW)
t_{1hr} = # of time steps that equals 1 hour (e.g. if time step is 5 min then t_{1hr} = 60 / 5 = 12)

To determine the system round-trip efficiency, the energy discharged by the energy storage system during a profile is summed for all three repeated cycles and divided by the sum of the energy charged for the same three cycles, shown in Equation 3.

$$SyS_{RTE} = \frac{\sum_{i=1}^{X} E_{d,kWh}(i)}{\sum_{i=1}^{X} E_{c,kWh}(i)} \qquad \text{Equation 3}$$

Parameters:

SyS_{RTE} = System Round Trip Efficiency
$E_{d,kWh}(i)$ = Energy discharged during i^{th} cycle test (kWh)
$E_{c,kWh}(i)$ = Energy charged during i^{th} cycle test (kWh)
X = number of cycle tests

Also recorded during the tests were the voltage harmonics on one of the two strings. To meet the IEEE 519, the voltage total harmonic distortion has to be less than 5%.

Table 4 - System Capacity Test Results

Test	Cycle	Discharge Duration	Power Command (kW)	Energy Performance (kWh)	System Round Trip Efficiency (%)	Max V_{THD} (%)
1	1	6.2	520	3,225.05	66.27	2.49
1	2	6.2	520	3,218.64	66.12	2.49
1	3	6.2	520	3,218.003	67.11	2.69
2	1	4	640	2,561.46	68.58	2.21
2	2	4	640	2,572.64	66.52	2.19
2	3	4	640	2,562.08	66.26	2.14
3	1	2	1000	2,004.05	64.82	2.56
3	2	2	1000	2,003.00	59.19	2.61
3	3	2	1000	2,018.73	61.92	2.60

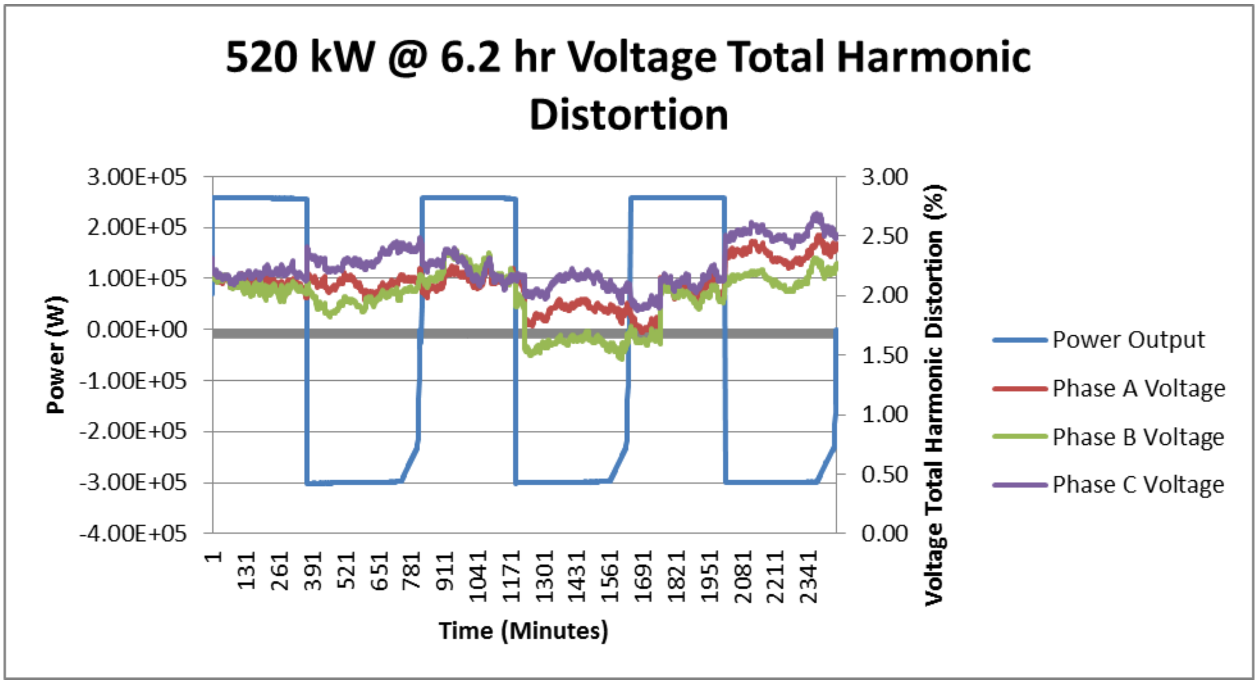

Figure 8 - 520 kW @ 6.2 hr Voltage Total Harmonic Distortion for Single String

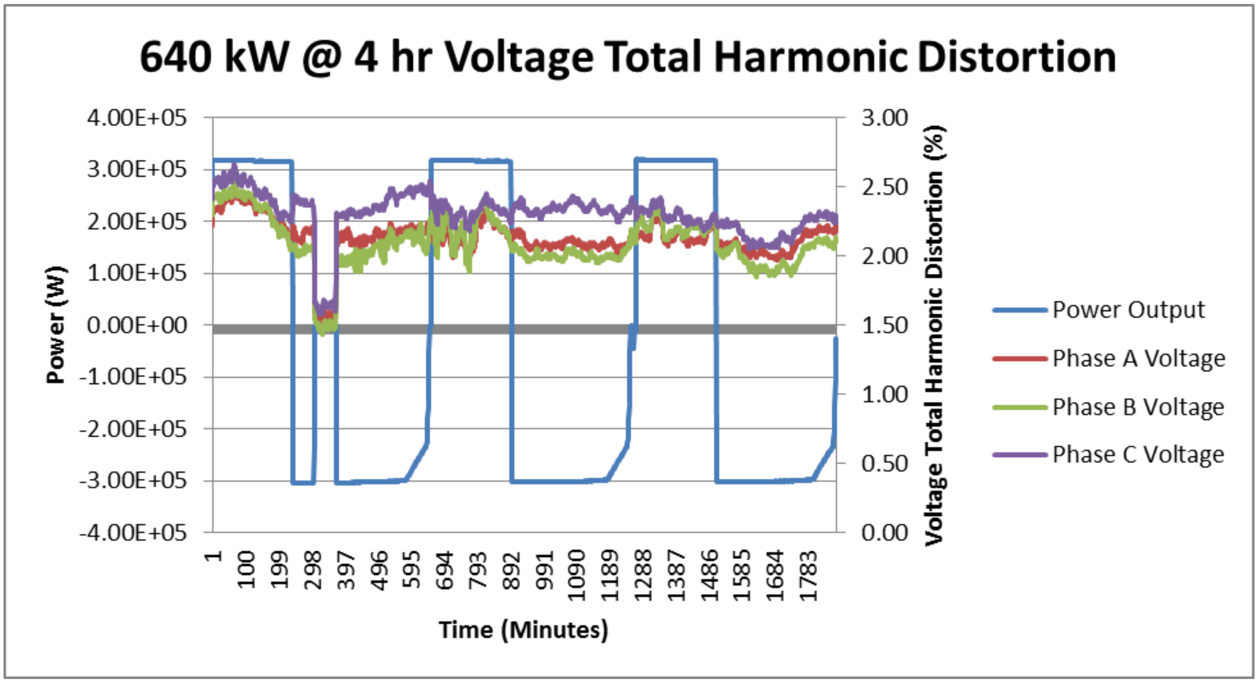

Figure 9 - 640 kW @ 4 hr Voltage Total Harmonic Distortion for Single String

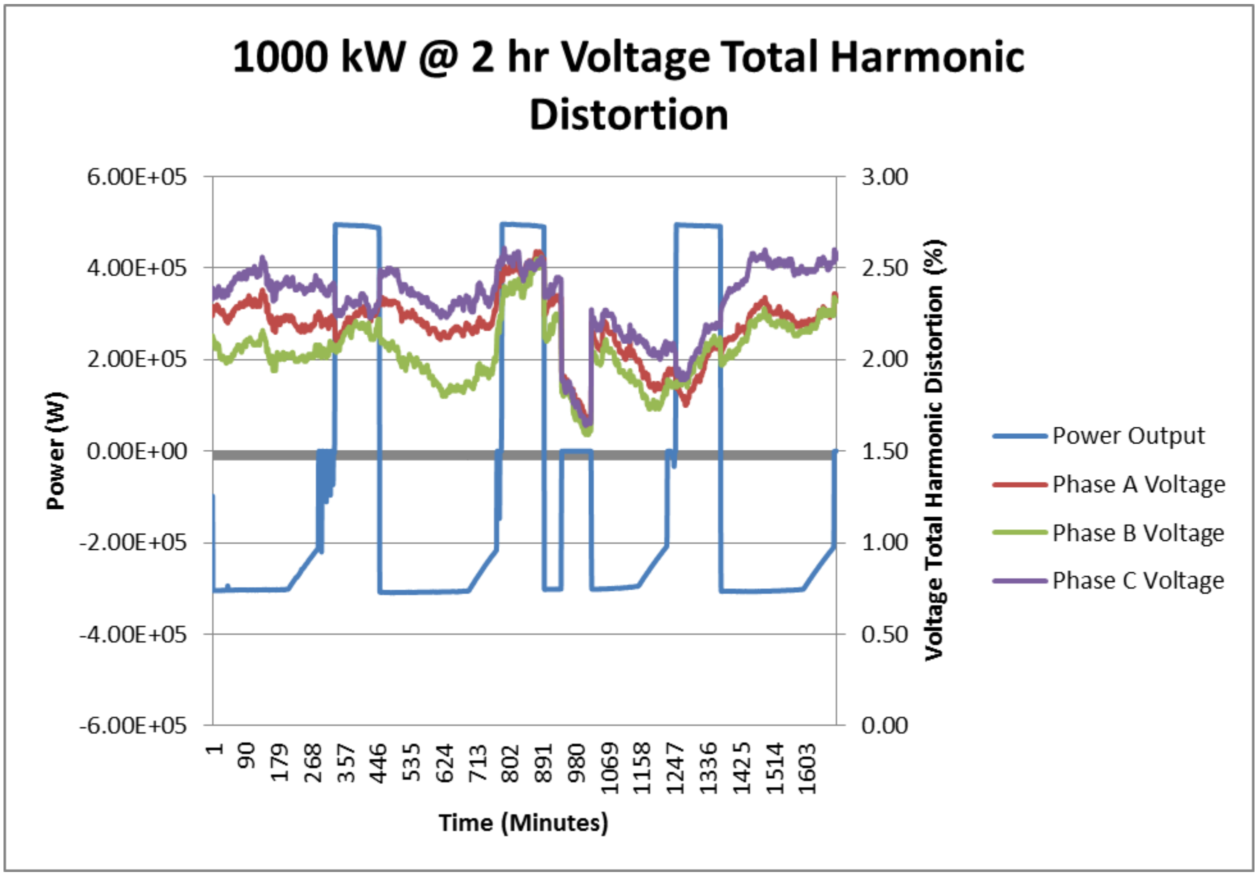

Figure 10 - 1000 kW @ 2 hr Voltage Total Harmonic Distortion for Single String

4. USE CASE TEST PROTOCOL

There were two Use Case tests performed; frequency regulation and peak shaving management. In the frequency regulation Use Case, the duty cycle for the energy storage ranges from -100% kW rated discharge of the system to 100% kW rated charge of the system and the change of power command is done every 4 seconds. This is based on the dynamic regulation signal from PJM for April 2011 to March 2012, shown in
Figure **11**, used in the PNNL/SNL test protocol. The Uni.System™ has a maximum charge rate that is limited to approximately 960 kW, therefore, the system will experience a slight increase in the time the balance signal is not tracked. The UET has stated that the Uni.System™ power tracking has a +/- 0.5% at rated power of 600 kW per battery string which is +/- 3 kW.

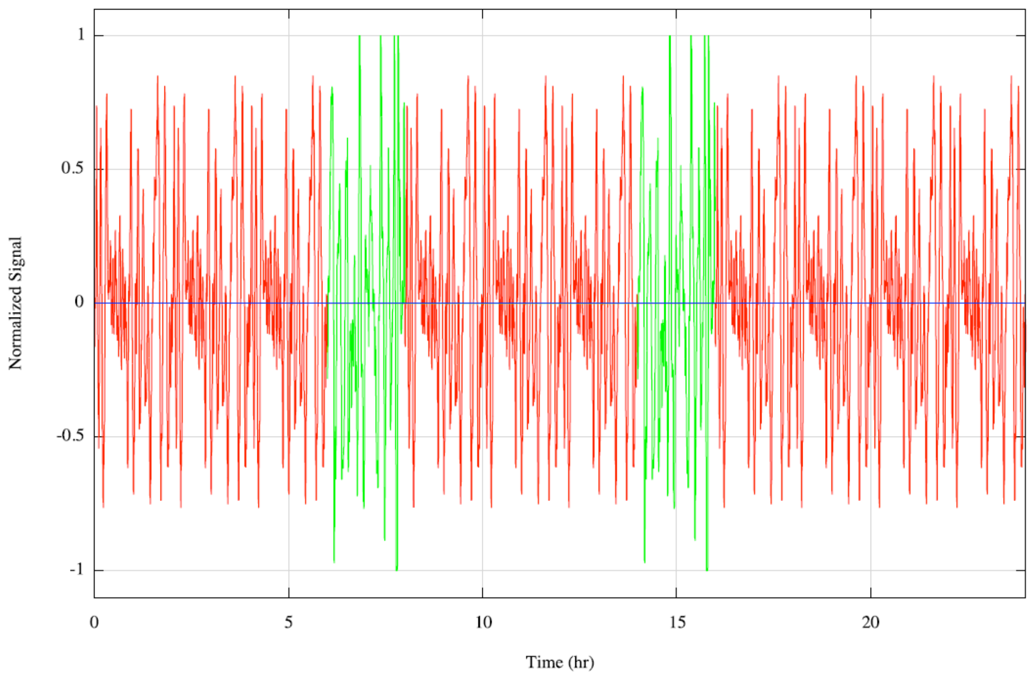

Figure 11 - Dynamic PJM Regulation Signal used in the PNNL/SNL Test Protocol

The second Use Case is peak shaving management, which is when the energy storage is applied for one or more of the following: energy time shift (arbitrage), electric supply capacity, load following, transmission congestion relief, distribution system upgrade deferral, transmission system upgrade deferral, retail demand charge management, wind energy time shift (arbitrage), base load time shift, photovoltaic energy time shift (arbitrage) and renewable capacity firming. For this Use Case, the energy storage is to follow the PNNL/SNL test protocol by cycling the energy storage with each cycle having a 12-hour charge window, a variable duration discharge window and two equal float windows that bring the total cycle duration to one 24-hour period. Based on system specification, an 8-hour charge time is sufficient so the cycle tests will have longer rest periods between. The three cycles tested are shown in the figures below.

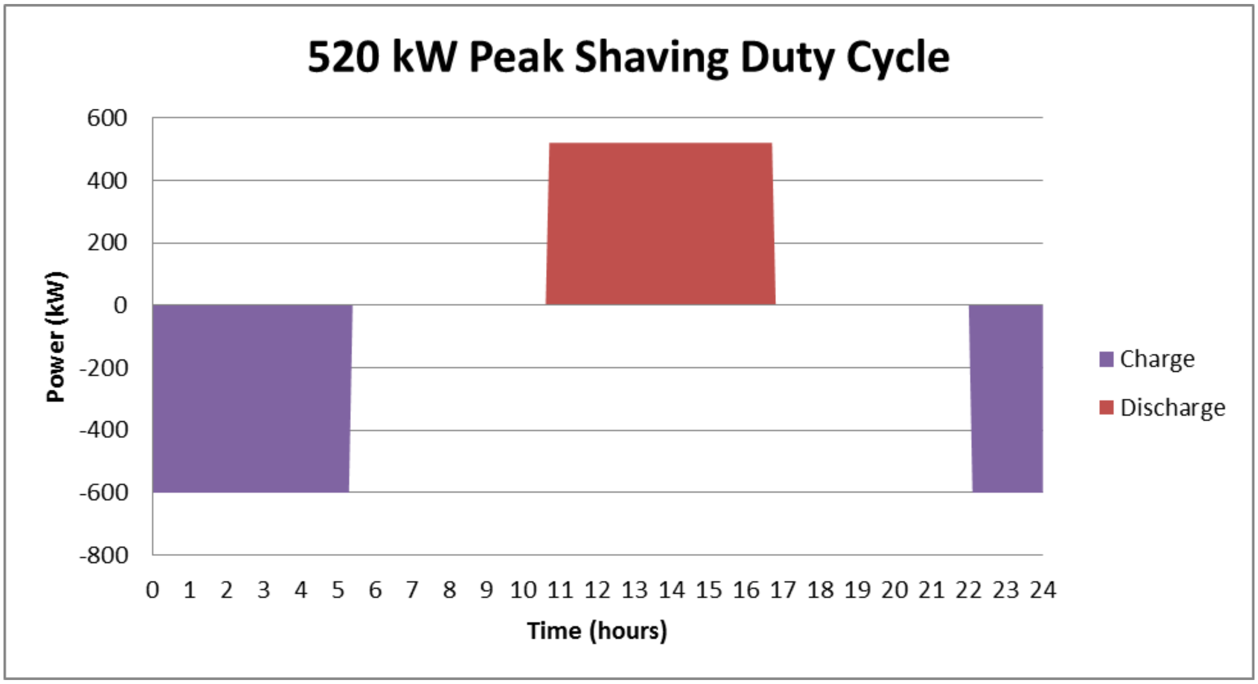

Figure 12 - Peak Shaving 520 kW Duty Cycle

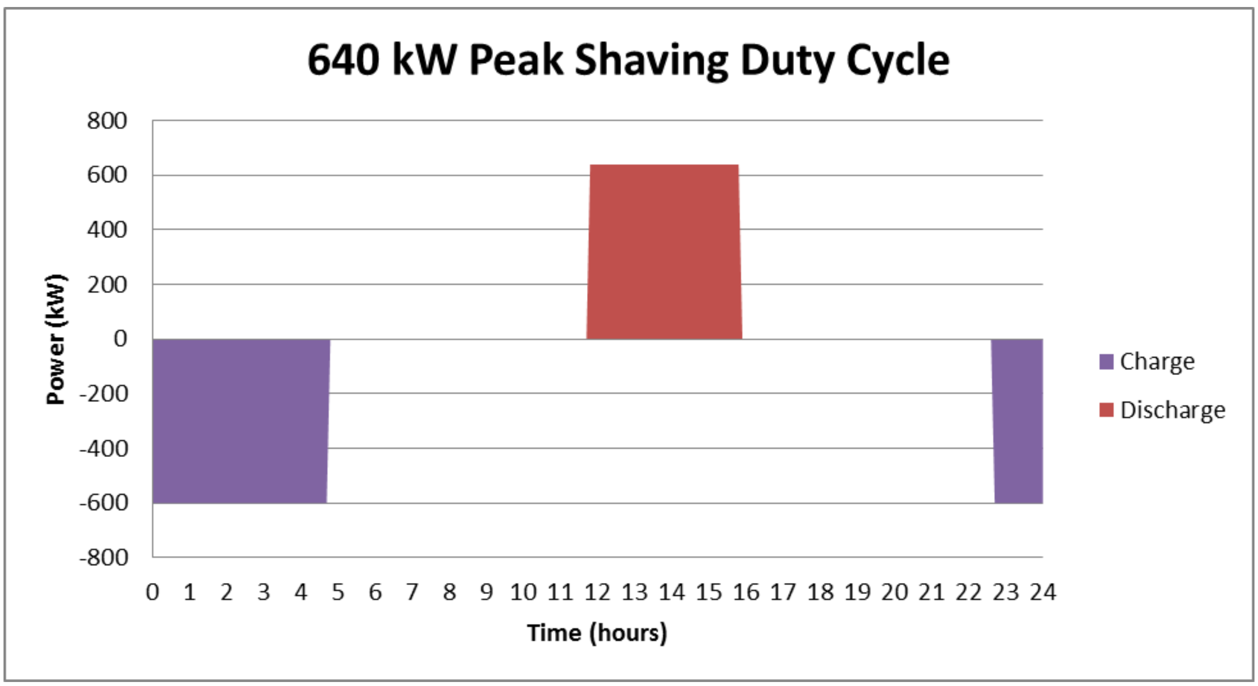

Figure 13 - Peak Shaving 640 kW Duty Cycle

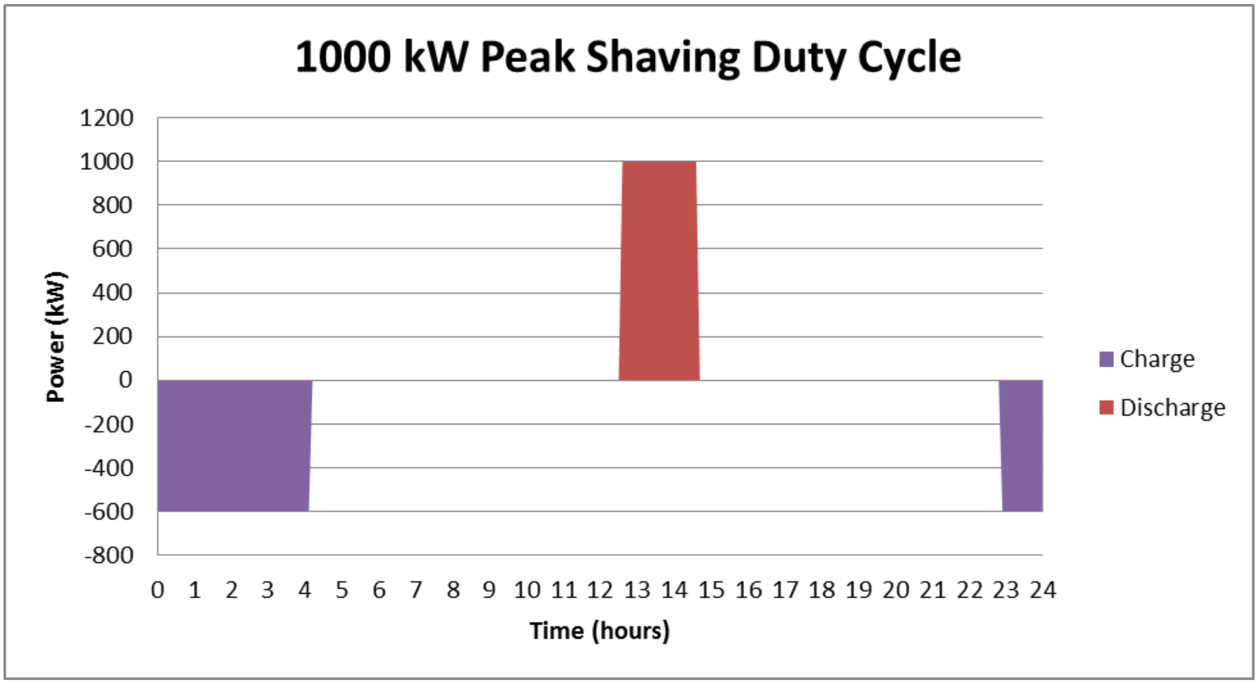

Figure 14 - Peak Shaving 1000 kW Duty Cycle

For both use cases, the test procedures along with the results are reported.

4.1. Frequency Regulation Test Procedure

1. Charge or discharge Uni.System™ to a certain SOC determined by UET and hold for 15 minutes before frequency regulation signal begins
2. Program and start the frequency regulation signal shown in Figure 11 using the site controller
3. Record Start time of test
4. After following the frequency regulation signal for 24 hours, recharge the Uni.System™ back to original SOC to provide data for a roundtrip efficiency calculation
5. Record time and verify that data has been captured by the OSI PI data historian

4.2. Frequency Regulation Test Results

To calculate the system round trip efficiency for the frequency regulation test the total energy discharged is divided by the total energy charged. Energy calculations are shown in Equations 4 and 5 and then substituted into Equation 3.

$$E_{d,kWh} = \sum_{i=1}^{X} P_{kW}(i) * \frac{1}{t_{1hr}}, \; if \; P_{kW}(i) > 0 \qquad \text{Equation 4}$$

Parameters:

$E_{d,kWh}$ = energy produced during discharge
X = number of time steps in frequency regulation test (24 hours * 3600 second = 86,400 seconds)
$P_{kW}(i)$ = power produced by energy storage at time i, (kW)
t_{1hr} = # of time steps that equals 1 hour (3600 seconds / 4 seconds = 900)

$$E_{c,kWh} = \sum_{i=1}^{X} |P_{kW}(i)| * \frac{1}{t_{1hr}}, if\ P_{kW} < 0 \qquad \textbf{Equation 5}$$

Parameters:

$E_{c,kWh}$ = energy consumed during charge
X = number of time steps in frequency regulation test
$P_{kW}(i)$ = power consumed by energy storage at time i, (kW)
t_{1hr} = # of time steps that equals 1 hour (3600 seconds / 4 seconds = 900)

As part of the frequency regulation, the energy storage ability to respond to the reference signal during the 24-hour period is calculated using the squared sum of the residual between the signal command and energy storage output shown in Equation 6. Also calculated is the magnitude error between the reference signal and energy storage output in terms of power, discharge energy in a cycle and the charge energy in a cycle shown in Equations 7 and 8. To also determine how often the system is tracking the reference signal, the total time the system cannot follow the reference signal and percentage tracked is reported shown in Equation 9.

$$P_{ERR} = \sum_{i=1}^{X} (P_{SIGNAL}(i) - P_{ESS}(i))^2 \qquad \textbf{Equation 6}$$

Parameters:

P_{ERR} = sum of the square of errors between the balancing signal and the power delivered or absorbed by the ESS
X = number of time steps in frequency regulation test
$P_{SIGNAL}(i)$ = power command from balancing signal (kW)
$P_{ESS}(i)$ = power delivered or absorbed by the energy storage (kW)

$$P_{ERR,MAG} = \sum_{i=1}^{X} |P_{SIGNAL}(i) - P_{ESS}(i)| \qquad \textbf{Equation 7}$$

Parameters:

$P_{ERR,MAG}$ = sum of the absolute magnitude of the difference between the balancing signal and the power delivered or absorbed by the ESS (kW)
X = number of time steps in frequency regulation test
$P_{SIGNAL}(i)$ = power command from balancing signal (kW)
$P_{ESS}(i)$ = power delivered or absorbed by the energy storage (kW)

$$E_{ERR,MAG} = \sum_{i=1}^{X} |E_{SIGNAL}(i) - E_{ESS}(i)| \qquad \textbf{Equation 8}$$

Parameters:

$E_{ERR,MAG}$ = sum of the absolute magnitude of the difference between the balancing signal and the power delivered or absorbed by the ESS (kWh)
X = number of time steps in frequency regulation test
$E_{SIGNAL}(i)$ = balance signal energy for a half cycle, with half cycle being the signal of the same sign (above or below the x-asis)
$E_{ESS}(i)$ = energy delivered or absorbed by the energy storage (kWh) for each half cycle

$$Sig_{TRACK} = \left(1 - \frac{t_{OFF}}{24}\right) * 100 \qquad \textbf{Equation 9}$$

$$Track = \left|\frac{P_{SIGNAL}(i)-P_{ESS}(i)}{P_{SIGNAL}(i)}\right| * \frac{100 * P_{ESS}(i)}{P_{100\%}} \quad \text{Equation 10}$$

$$t_{OFF} = \begin{cases} 0, if\ Track \leq 2\% \\ \sum_{i=1}^{X} t(i), otherwise \end{cases} \quad \text{Equation 11}$$

Parameters:

Sig_{TRACK} = portion of the balance signal that was tracked by the energy storage system (%)
$T_{off}(i)$ = total time the system cannot follow the signal (hours)
Track = error percent between the balance signal and the power delivered or absorbed normalized to the max power rating of the energy storage system
$P_{SIGNAL}(i)$ = power command from balancing signal (kW)
$P_{ESS}(i)$ = power delivered or absorbed by the energy storage (kW)
$P_{100\%}$ = rated max power of the system (kW)
t(i) = time when Track is greater than 2% error in terms of hours

Table 5 - Frequency Regulation Test Results

Discharge Energy (kWh)	Charge Energy (kWh)	Recharge Energy to charge back to SOC (kWh)		Round Trip Efficiency (%)
3,860.02	-4,650.92	-1,977.23		58.24
T_{OFF} (hours)	P_{ERR}	$P_{ERR,MAG}$ (kW)	$E_{ERR,MAG}$ (kWh)	Sig_{TRACK}(%)
0.24	1,510,453,673	881,394.02	184.00	99.01

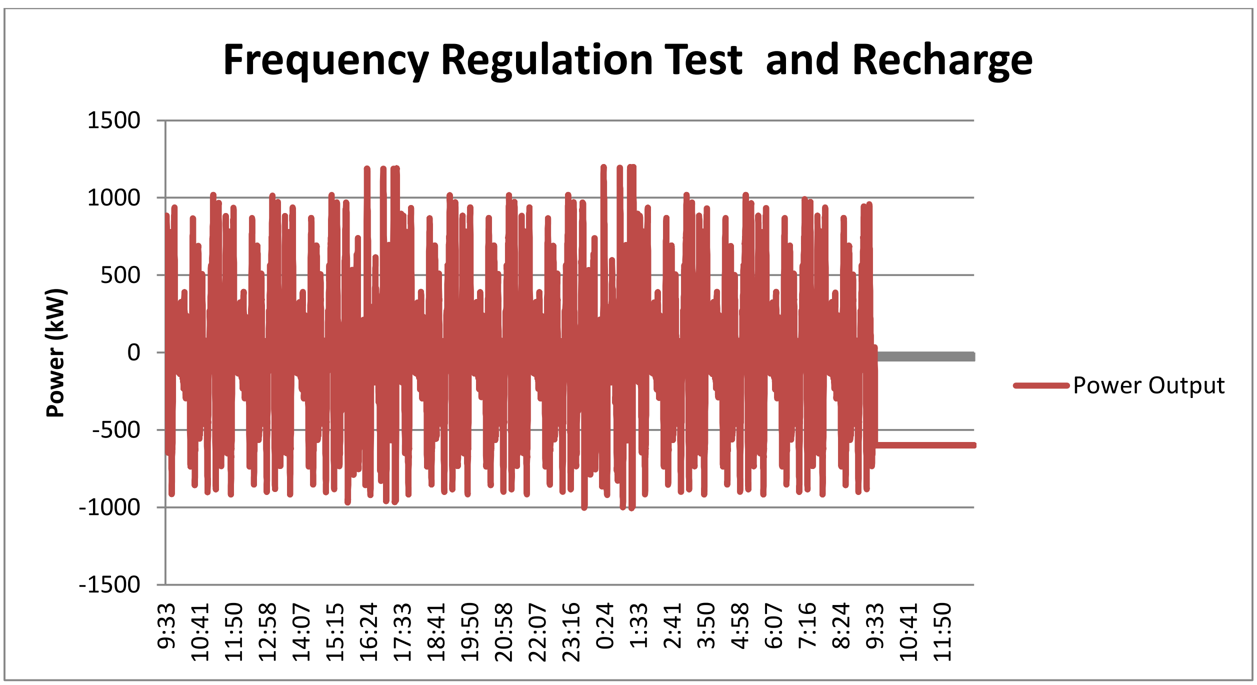

Figure 15 - Frequency Regulation and Recharge

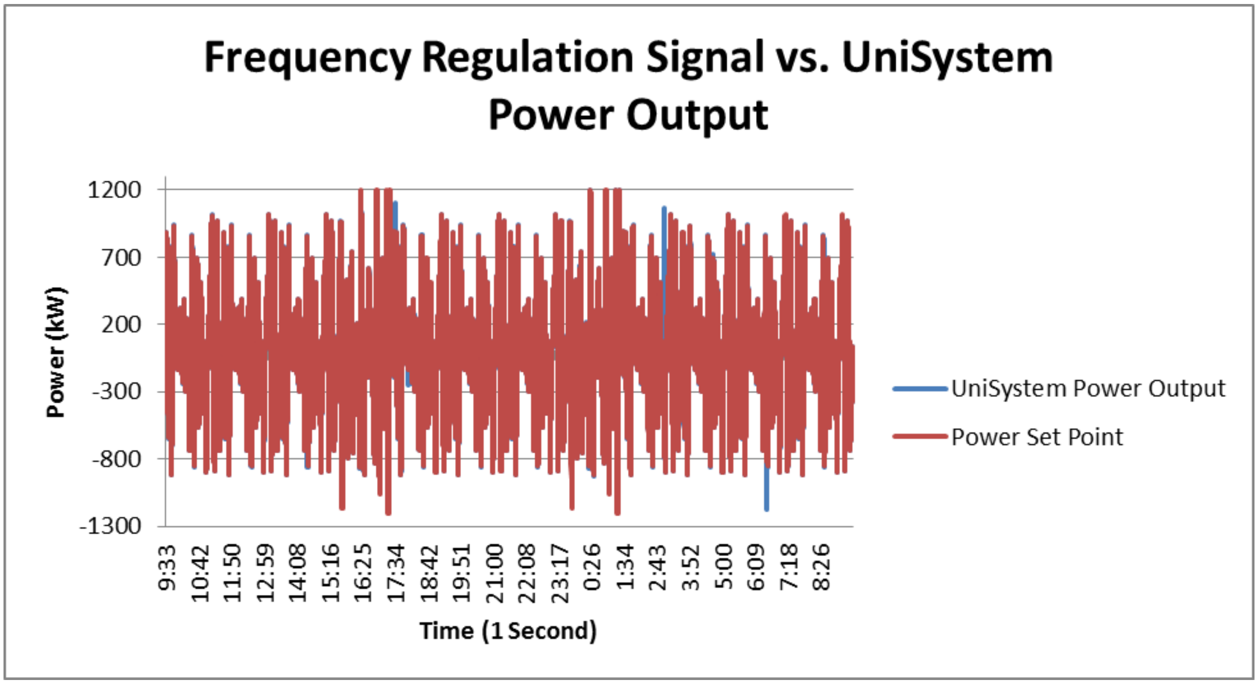

Figure 16 - Frequency Regulation Signal vs. Uni.System™ Power Output

4.3. Peak Shaving Test Procedure

1. Charge Uni.System™ to 100% SOC
2. Program and start the 520 kW duty cycle shown in Figure 12 using the site controller
3. Record Start time of test
4. After 520 kW duty cycle, recharge the Uni.System™ back to 100% SOC to provide data for a roundtrip efficiency calculation
5. Record time and verify that data has been captured by the OSI PI data historian
6. Program and start the 640 kW duty cycle shown in Figure 13 using the site controller
7. Record Start time of test
8. After 640 kW duty cycle, recharge the Uni.System™ back to 100% SOC to provide data for a roundtrip efficiency calculation
9. Record time and verify that data has been captured by the OSI PI data historian
10. Program and start the 1000 kW duty cycle shown in Figure 14 using the site controller
11. Record Start time of test
12. After 640 kW duty cycle, recharge the Uni.System™ back to 100% SOC to provide data for a roundtrip efficiency calculation
13. Record time and verify that data has been captured by the OSI PI data historian

4.4. Peak Shaving Test Results

Table 6 - Peak Shaving Management Test Results

Duty Cycle	8 Hours Charge Window + Off Time							
	Charge Time (hr)	Power (kW)	Charge Energy (kWh)	Aux Energy During Charge (kWh)	Aux Energy During Off Time (kWh)	Net Consumed Energy (kWh)	Rest Time (hr)	Max V_{THD} (%)
A	7.5	-600	-12,917.10	-697.04	-2.7	-13,616.90	5.2+5.3	2.69
B	6.2	-600	-10,302.50	-560.91	-15.41	-10,878.80	6.9 + 6.9	2.54
C	5.5	-600	-8,868.67	-522.36	-16.23	-9,404.26	8.2 + 8.3	2.56
Duty Cycle	Discharge window at different duration							
	Discharge Time (hr)	Power (kW)	Discharge Energy (kWh)	Aux Energy During Discharge (kWh)	Net Delivered Energy (kWh)	System Round Trip Efficiency (%)		Max V_{THD} (%)
A	6.2	520	9,661.74	606.83	9,054.91	66.50		2.42
B	4	640	7,696.18	396.39	7,299.79	67.10		2.66
C	2	1000	6,025.87	209.45	5,816.43	61.85		2.61

Results in Table 6 are the sum of all 3 repeated tests for each duty cycle. In the following figures, the power outputs are shown.

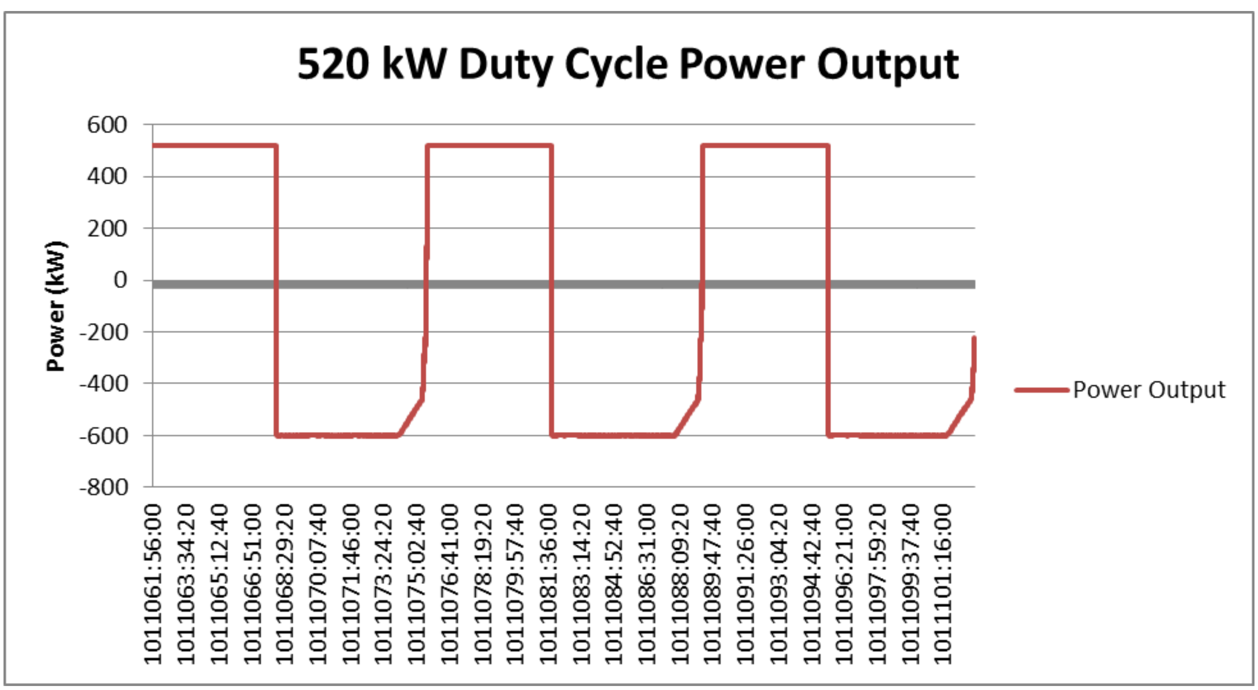

Figure 17 - 520 kW Duty Cycle Power Output

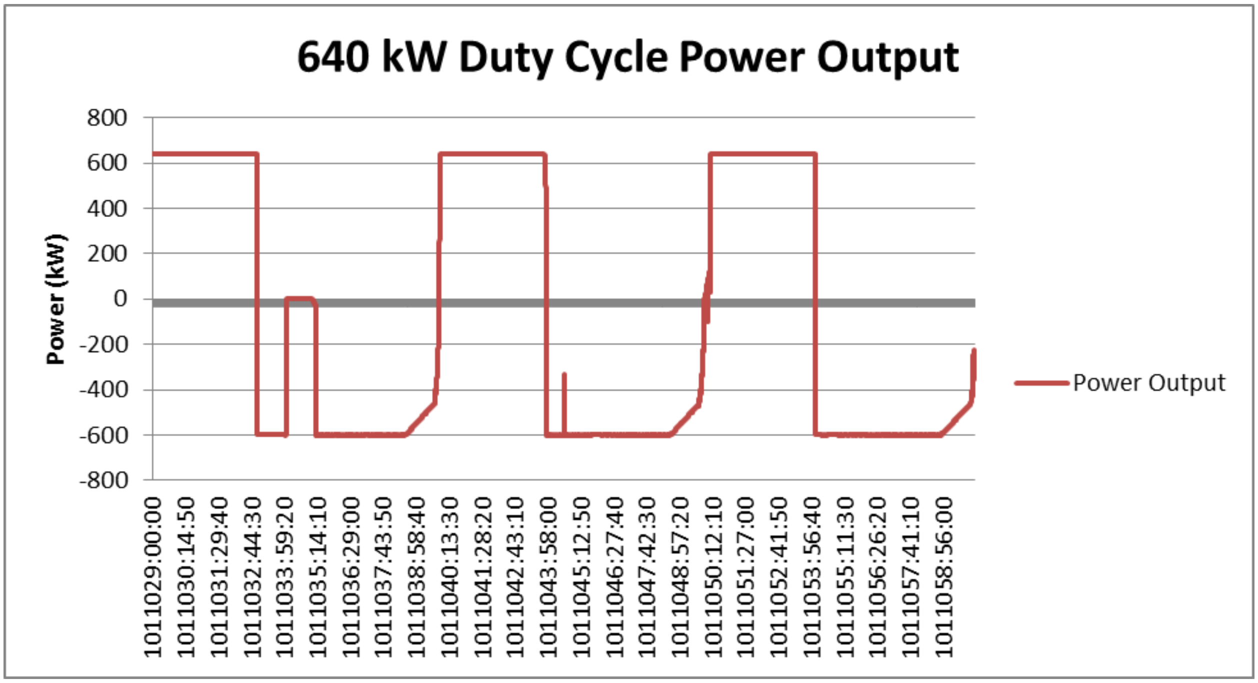

Figure 18 - 640 kW Duty Cycle Power Output

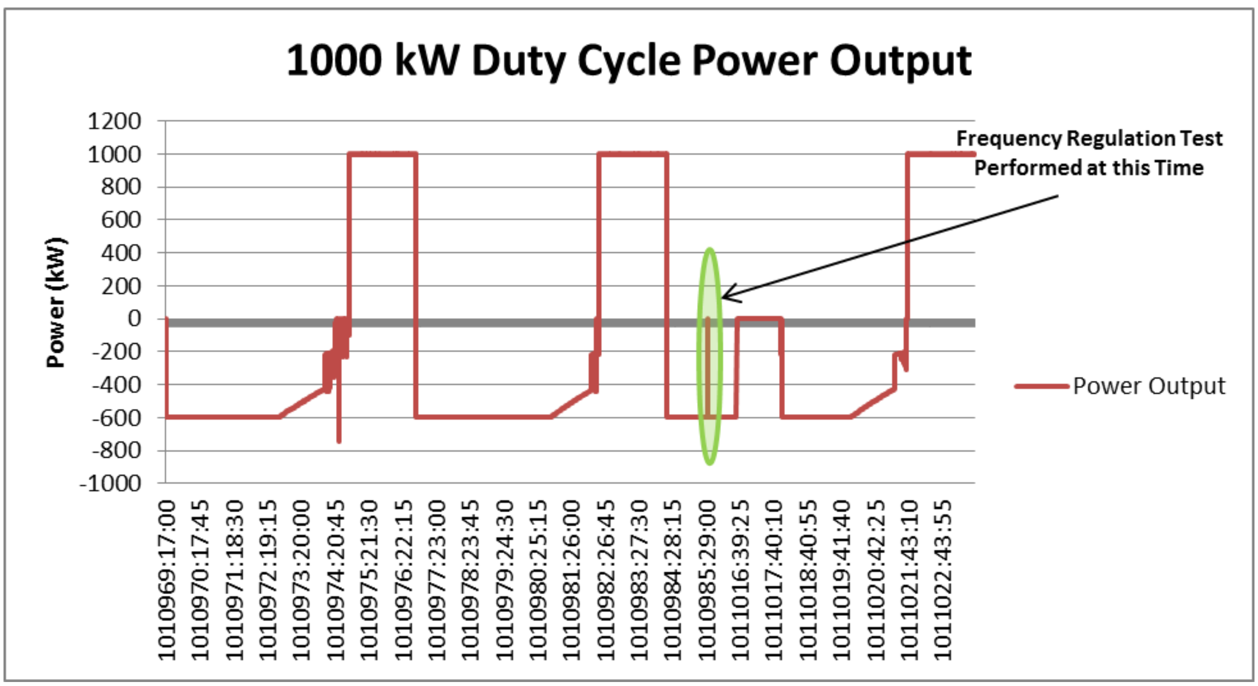

Figure 19 - 1000 kW Duty Cycle Power Output

5. THD TESTING

THD testing was not a requirement of the witness testing but was added since testing was ahead of schedule and a power quality meter was available. In order to capture the harmonic output of the Uni.System™, an additional test was performed in which different charge and discharge rates were performed. The power ratings for the charge cycles were 800 kW, 600 kW and 300kW. Power ratings for the discharge cycles were 1200 kW, 900 kW, 600 kW and 300 kW. These ratings were selected based on the maximum charge and discharge limits as well as performing at a low power output which is 25% of nameplate rating. Since there was only one Hioki 9624-50 meter available, only one string was measured.

In order to calculate the Total Demand Distortion, the short circuit current (I_{sc}) is needed as stated in IEEE 519-1992 table shown in Figure 20. Since the I_{sc} for the Uni.System™ has not been determined by UET at this time, a value of 2 p.u. of the rated PCS current will be used. The PCS rated current is 1200A so the I_{sc} is calculated to be 2400A. If the I_{sc} is calculated to be higher than 2 p.u. of the rated current, the allowable TDD will increase.

Current Distortion Limits for General Distribution Systems
(120 V Through 69000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited to 25% of the odd harmonic limits above.						
Current distortions that result in a dc offset, e.g. half-wave converters, are not allowed.						
* All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.						

Where

I_{sc}	= maximum short-circuit current at PCC.
I_L	= maximum demand load current (fundamental frequency component) at PCC.
TDD	= Total demand distortion (RSS), harmonic current distortion in % of maximum demand load current (15 or 30 min demand).
PCC	= Point of common coupling.

Figure 20 - IEEE 519-1992 Harmonic Current Limits [1]

The lowest power output during the test is 25% of the rated power of one string which is 150kW. Voltage for the PCS is 283 V_{ac} and calculating the current for 150 kW using the PCS voltage is 306 A. The largest I_{sc}/I_L is 7.84 which the first row in the IEEE 519-1992 Harmonic Current Limits will be used which the TDD needs to be less than 5%. Also in accordance to the IEEE 519-1992 standard, the total voltage harmonic distortion has to be less than or equal to 5%.

5.1. THD Testing Procedure

1. Discharge or charge Uni.System™ to a certain SOC determined by UET which allows the system to operate both directions
2. Using the Site Controller, set the power command to -66.67%
3. Record Start time of test
4. After at least 5 minutes with the Uni.System™ charging at -66.67%, change the power command in the Site Controller to -50%
5. After at least 5 minutes with the Uni.System™ charging at -50%, change the power command in the Site Controller to -25%
6. After at least 5 minutes with the Uni.System™ charging at -25%, change the power command in the Site Controller to 100% placing the Uni.System™ into discharge mode
7. After at least 5 minutes with the Uni.System™ discharging at 100%, change the power command in the Site Controller to 75%
8. After at least 5 minutes with the Uni.System™ discharging at 75%, change the power command in the Site Controller to 50%
9. After at least 5 minutes with the Uni.System™ discharging at 50%, change the power command in the Site Controller to 25%
10. Record time and verify that data has been captured by the Hioki 9624-50

5.2. THD Testing Results

As seen in Table 7, all the harmonics created by the Uni.System™ are well below the IEEE 519-1992 limits. Figure 21, Figure 22 and Figure 23 show the power output, total voltage harmonic distortion and total current demand distortion for the entire THD test.

Table 7 - Result Matrix for THD Testing for String 2

% of Max Power (%)	Average Power Output (kW)	Maximum V_{THD} (%)	Maximum I_{TDD} (%)
-66.67	-394	2.48	3.29
-50	-302	2.41	3.16
-25	-151	2.4	3.18
100	593	2.68	3.33
75	447	2.69	2.94
50	298	2.69	2.94
25	149	2.53	3.30

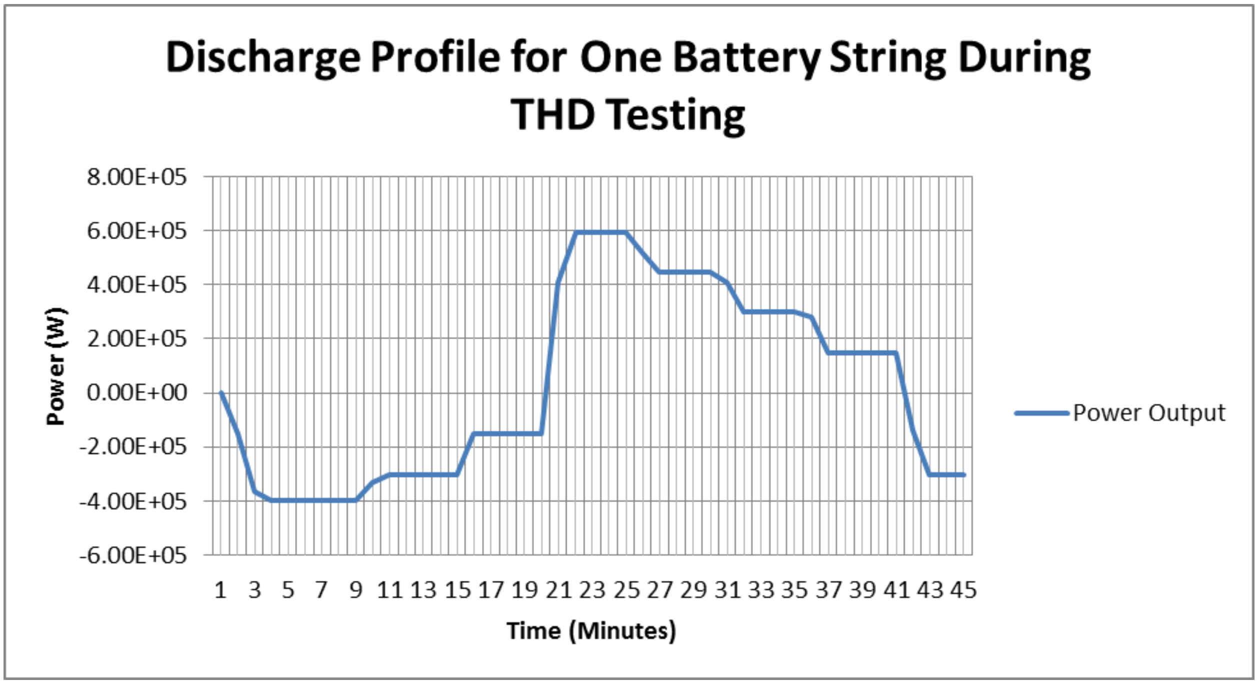

Figure 21 - Power Output during THD Testing for One Uni.System™ String

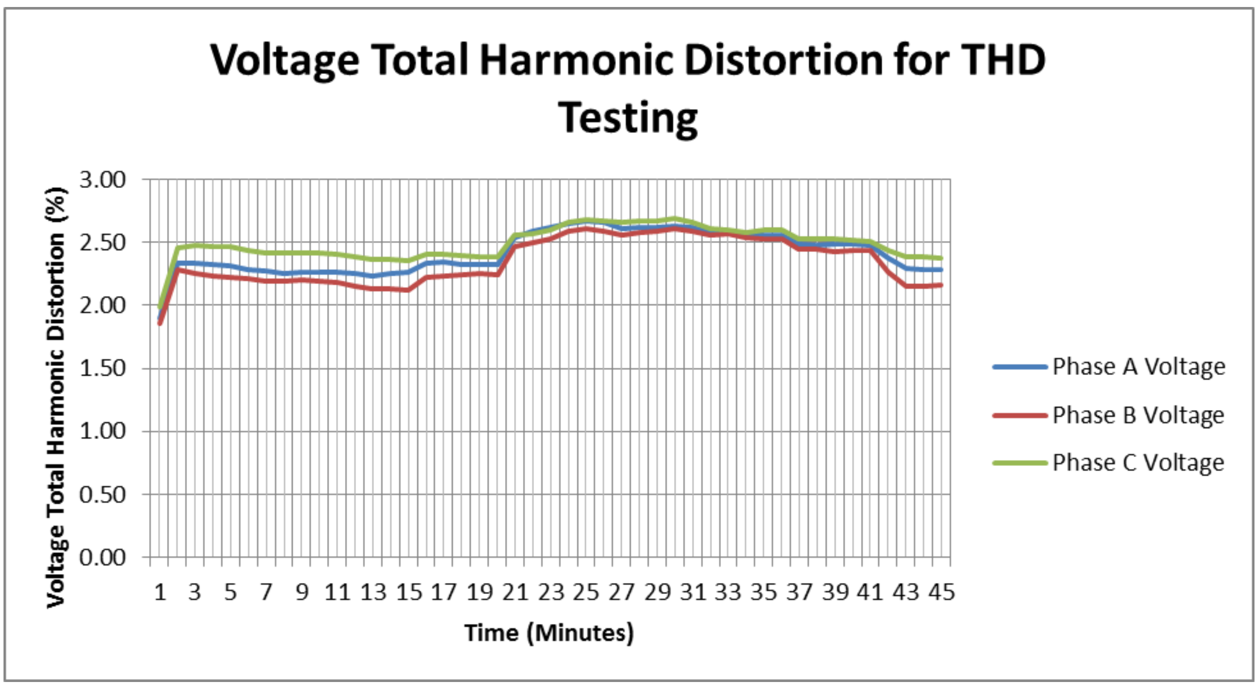

Figure 22 - Voltage Total Harmonic Distortion for THD Testing

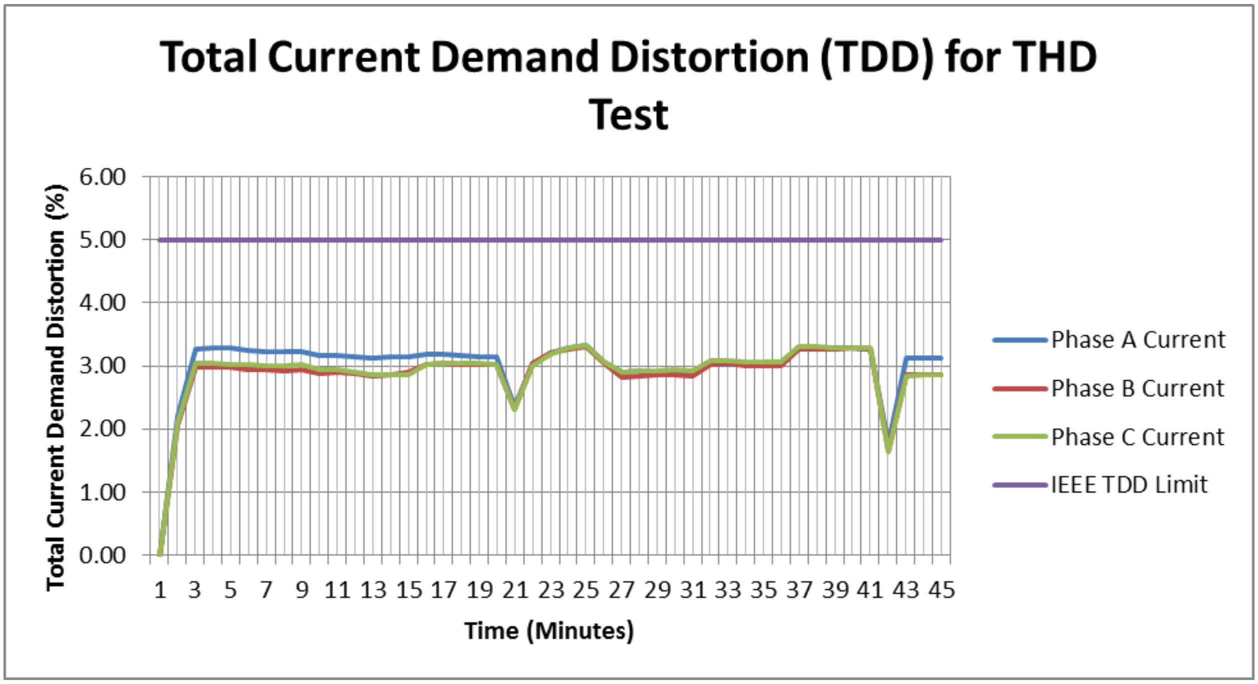

Figure 23 - Total Current Demand Distortion for THD Testing

6. CONCLUSION

The Uni.System^{TM} installation at Pullman, WA has proper personal protective equipment, safety documentation, hazard signs, hazard mitigation and emergency response equipment for a safe environment for personnel working around the site, which was physically verified by Sandia. There are also alarms in place with constant monitoring of multiple sensors that allow Avista and UET to be informed of the status of the Uni.System^{TM} and any problems 24 hours, 7 days a week. Besides the monitoring equipment, all data recording equipment including meters and communication back to UET headquarters was verified by Sandia and is adequate to provide accurate and sufficient data to calculate the Uni.System^{TM} performance.

Sandia has verified that the Uni.System^{TM} can produce up to at least 3.2 MWh which was achieved when the 520 kW continuous power output during the cycle test was performed. Cycle and peak shaving test performed also verified that the rated power can produce 1 MW for 2 hours, 640 kW for 4 hours and 520 kW for 6.2 hours with energy capacity still available in the Uni.System^{TM}. The 65-70% efficiency was achieved when the Uni.System^{TM} was continuously delivering up to 640 kW, but dropped to approximately 60% when the continuous power delivered was rated at a power of 1 MW. During the frequency regulation, the efficiency was 58.24%. Since the test revealed low roundtrip efficiency during the frequency regulation test, UET retested the frequency regulation signal with another method to increase the efficiency number. The new method added some offset on the charge signal to get rid of the following recharge at the end of the frequency regulation test. By doing this, UET reports that the roundtrip efficiency increased to approximately 75%. Sandia did not verify this new method tested during the frequency regulation test and cannot be confirmed. DC voltage range of 465 Vdc – 1000 V_{dc} at the PCS was not recorded in this report but was verified through data that was collected through the OSI software.

Part of the Uni.System^{TM} performance specification was that the power control modes of dispatch and autonomous are available. Dispatch mode was verified as UET set the Uni.System^{TM} to discharge and charge at 50% rated power through the HMI and site controller performed while Sandia was at the site. Autonomous mode was demonstrated through all the tests since a programmed power output profile was created in Microsoft Excel and sent to the site controller. The site controller would automatically change the power set point for the Uni.System^{TM} according to the power output profile with no human interaction.

Performance specifications that still need to be verified are the self-discharge of less than 2 % in standby mode, response time of 50 ms and operational ambient temperature range of -40°c to 50°c. Self-discharge of less than 2% is a test that needs long durations to verify. However, the self-discharge is limited only to the residual volume of electrolyte isolated in the stacks and no self-discharge of energy is happening in the electrolyte remaining in the tanks. As the Uni.System^{TM} continues to provide service for Avista, the data can be collected and self-discharge calculated. Maximum and minimum operational temperatures are typically verified during the prototype phase and possibly the factory acceptance utilizing temperature changing equipment such as temperature chambers. Response time test requires data collection equipment that is twice as fast as the stated response time and multiple input channels so the power signal and the power output can be captured. In this case, the data would need to be collected at 25 ms or faster to verify the response time. A power quality meter was available at the time of testing that had a fast enough sampling rate to capture the response time but did not have enough input channels to capture both the power signal command and the power output. In the future, the response test needs to be completed and verified.

Even though these performance specifications were not verified, the Uni.System^{TM} adequately passed the tests designed around the peak shaving and frequency regulation services.

7. REFERENCES

[1] IEEE , "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," Vols. ISBN 1-55937-239-7, 1993.

[2] K. Bray, D. Conover, S. Ferreira and D. Rose, "Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems," Pacific Northwest National Laboratory, October 2012.

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